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Evaluation of Overall Thermal Transfer Value (*OTTV*) for commercial buildings constructed with green roof

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HIGHLIGHTS

- ▸ Correction factors ranging from 0.03 to 0.99 were derived for *OTTV* evaluation of building with green roof.
- ▸ An experimental setup of green roof was constructed on the rooftop of a building.
- ▸ Field measurement was conducted in the green roof system.
- ▸ Computer simulation model (EnergyPlus with Ecoroof) was validated using experimental data of the green roof.

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ABSTRACT

Overall Thermal Transfer Value (*OTTV*) is a measure of average heat gain into a building through the building envelope. It is a widely adopted measure in many countries for enhancing energy-efficient building design. In the past decade, there is increasing application of green roof into commercial buildings for enhanced building insulation, leading to reduction in heat gain through the roof area as well as cooling requirement of a building. Since the current *OTTV* equations and coefficients were originally developed for buildings with traditional bare roof construction, building designers have difficulty to compute the *OTTV* for building constructed with green roof. The aim of this study is to revise the existing *OTTV* calculation method and derive a set of correction factors for *OTTV* evaluation of green roof integrated buildings. An experimental setup of a green roof system with sensors was installed on the rooftop of a commercial building. The measured data were used for validation of a building energy simulation program EnergyPlus incorporated with a green roof model Ecoroof. Four building cases with typical and traditional roof constructions were modeled using the validated computer simulation program. Through a series of parametric computer simulations, a correlation between *OTTV* and annual heat gain through the roof area was established with that a set of correction factors ranging from 0.03 to 0.99 was developed. Theses correction factors can be used by building designers to compute the *OTTV* of building constructed with green roof. The details of methodology and findings are reported in this paper.

1. Introduction

In recent years, there is cooperative effort to reduce greenhouse gas (GHG) emission all over the world. The main objective is to pursue a blue sky and healthy environment for sustainable development of a society. Minimization of energy use is one of the keys to foster GHG reduction. Building, as one of the largest electricity consumers, can make a marked contribution to energy conservation as well as GHG removal by sophisticated building design.

Currently there are two major types of building energy codes, namely prescriptive and performance-based energy codes, widely adopted in the building industry for governing energy-efficient building/building services system design. In Hong Kong, five prescriptive energy codes have been published by the local government as listed below [1–5]:

i. Code of Practice for Energy Efficiency of Lighting Installations.
ii. Code of Practice for Energy Efficiency of Air Conditioning Installations.
iii. Code of Practice for Energy Efficiency of Electrical Installations.
iv. Code of Practice for Energy Efficiency of Lift & Escalator Installations.
v. Code of Practice for Overall Thermal Transfer Value in Buildings.

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Nomenclature

A_f	area of fenestration (m^2)
A_r	area of opaque roof (m^2)
A_w	area of opaque wall (m^2)
CF	correction factor
ESM	external shading multiplier
H_f	foliage sensible heat flux (W/m^2)
H_g	ground sensible heat flux (W/m^2)
$I_{ir}^{\downarrow}$	total incoming long-wave radiation (W/m^2)
$I_s^{\downarrow}$	total incoming short-wave radiation (W/m^2)
L_f	foliage latent heat flux (W/m^2)
L_g	ground latent heat flux (W/m^2)
$OTTV_{i,BR}$	*OTTV* of a bare roof of a building case *i*
SC	shading coefficient of fenestration
SF	solar factor for vertical surface (W/m^2)
T_f	foliage temperature (K)
T_g	ground surface temperature (K)
TD_{EQr}	equivalent temperature difference for opaque roof (°C)
TD_{EQw}	equivalent temperature difference for opaque wall (°C)
U_r	thermal transmittance of opaque roof (W/m^2 °C)
U_w	thermal transmittance of opaque wall (W/m^2 °C)
$X_{exp,i}$	surface temperature (°C) at or heat flux (W/m^2) through a bare roof/green roof at hour *i* measured from experiment
$X_{sim,i}$	surface temperature (°C) at or heat flux (W/m^2) through a bare roof/green roof at hour *i* simulated by EnergyPlus
z	height or depth (m)

Greeks

ΔT_{win}	temperature difference for window glass (°C)
α_f	albedo (short-wave reflectivity) of the canopy
α_g	albedo (short-wave reflectivity) of ground surface
α_r	absorptivity of opaque roof
α_w	absorptivity of opaque wall
ε_f	emissivity of canopy
ε_g	emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_g\varepsilon_f$
κ	soil thermal conductivity of the surface (W/mK)
σ	Stefan–Boltzmann constant
σ_f	fractional vegetation coverage

Subscripts

i	building case A, B, C or D
j	soil thickness (m)
k	height of plant (m)
l	Leaf Area Index (*LAI*)
m	calendar month (from April to October)

Prescriptive building energy codes are simple and can provide a straightforward approach for building designers to evaluate the compliance of a building/building services system design with the energy codes.

On the other hand, performance-based building energy code is an alternative path to the prescriptive codes [6]. It considers the various components of building energy consumption, allowing trade-off among them. This approach provides rooms to building designers for innovative design. It focuses on the total energy consumption of a building design which is termed as Design Energy. A corresponding reference building (having the same size and shape as the design building) that fully complies with all the prescriptive building energy codes can be developed and its total energy consumption is calculated as Energy Budget. The performance-based building energy code is deemed to be complied if the Design Energy is smaller than or equal to the Energy Budget. No matter which approach is adopted, the Overall Thermal Transfer Value (*OTTV*) is a basic requirement that a building design must fulfill.

1.1. Development of OTTV control

The use of *OTTV* was firstly proposed by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) in 1975 [7]. It is a measure of the average heat gain into a building through the building envelope and can be used for comparing the thermal performance of buildings. There are three major components involved in the *OTTV* calculation: (i) conduction through opaque wall, (ii) conduction through fenestration, and (iii) solar radiation through fenestration. It is usual to have two sets of *OTTV* for a building, namely *OTTV* for external walls ($OTTV_{wall}$) and *OTTV* for roof ($OTTV_{roof}$). The *OTTV* of an entire building is given by the weighted average of the *OTTVs* of the external walls and the roof of a building.

In Asia, Singapore was the first country to develop an *OTTV* standard and regulatory control over the *OTTV* of air-conditioned buildings since 1979 [8,9]. Some other Asian countries including Philippines, Thailand, Malaysia and Indonesia also developed their *OTTV* standards in 1980s and 1990s [10–13].

In 2004, an *OTTV*-based energy estimation model for commercial buildings in Thailand was developed by Chirarattananon and Taveekun [14]. Simulation program DOE-2 was utilized to conduct a series of parametric runs to develop *OTTV* formulations for four different types of commercial buildings in Thailand. The resulting *OTTVs* were used in further parametric runs to develop a formulation for the cooling coil load and energy use of the commercial buildings. The results were expected to have contribution towards energy code compliance and energy monitoring.

Kunchornrat et al. proposed new parameters for *OTTV* calculation corresponding to the real climate zones in Thailand in 2009 [15]. The impacts of TD_{EQw} and ΔT_{win} were examined and proposed to the existing *OTTV* calculation. The study found that the new parameters could influence the *OTTV* of a reference building, which varied from 2.4% to 9.1% within different climate zones.

Chua and Chou refined the original *OTTV* equation adopted in Singapore and applied into residential buildings in 2010 [16]. They found that the original *OTTV* equation did not accurately account for the relative components of heat gains through the building envelope. By using Singapore's weather data consolidated for a particular year, three coefficients (TD_{EQw}, ΔT_{win} and *SF*) were derived by performing several multi-parametric simulations on two residential building types. An Envelope Thermal Transfer Value (*ETTV*) equation was then developed for the residential buildings in Singapore.

Research on *OTTV* in Hong Kong had been carried out by various local researchers. Chow & Chan had used DOE-2 program to conduct parametric studies to determine *OTTV* equations and coefficients for building envelopes in Hong Kong [17]. The window-to-wall ratio and orientation of building were varied in the study. They argued that heat transmission through the building envelope might reverse in direction during certain air-conditioned hours in a year. Therefore, two values of *OTTV*, one for the summer and the other for the winter season, had been established to account for seasonal changes in Hong Kong. The summer *OTTV*, calculated from the heat gain in hot season, was recommended as more appropriate for evaluating the thermal performance of building envelope in Hong Kong.